ADA

FINITE ELEMENT MODEL TO REDUCE FIRE AND BLAST VULNERABILITY

INTERIM REPORT
TFLRF No. 439

by
W. Loren Francis
Daniel P. Nicolella

Mechanical Engineering Division
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Southwest Research Institute® (SwRI®)
San Antonio, TX

for
David A. Tenenbaum

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD0014)

January 2013

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14. ABSTRACT Finite element models of the generic V-Hull and soldier were successfully integrated. Methodologies were developed to investigate the effects of structural component variations and safety measures on the risk of injury to the legs and lumbar. These models and software tools can now be used by the Army to evaluate future designs and improve current vehicle designs in an effort to improve occupant safety on and off the battlefield. Studies were performed to investigate the effects of material thickness on the lumbar and legs during an underbody blast event. A study was completed that determined the effects of foam on tibia forces during an under body blast event.						
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EXECUTIVE SUMMARY

Objectives

The objective of this effort is to develop a finite element model of a soldier to be used in identifying and exploring the benefits of safety enhancements in military vehicles. A finite element modeling and simulation assessment will identify key design parameters enabling improvements in design performance of existing and future tactical vehicles. Important scenarios include vehicular collisions, blast/fragment impact, and rollovers, as well as related hazards involving fuel and oil/fluid fires, carbon monoxide leakage, etc. The overall goal is to develop models and methodologies that may determine the relative importance and correlation of vehicle design factors and demonstrate how changes in these design factors can significantly increase the overall safety and survivability of occupants.

Importance of Project

The importance of this project is to develop a model and methodology that can be used by the Army to make informed design decisions on vehicles and restraints systems that will minimize the risk of injury to the occupants. By using the design variation studies along with the high fidelity soldier model, this approach can be applied to any vehicle in which models are available.

Technical Approach

A medical imaging database was identified and used to develop individual component finite element models. The component finite element models were combined into a finite element model of the soldier. For analyses, the structures of interest, such as legs or lumbar spine, were separated from the complete model and analyzed. A finite element model of the generic V-Hull vehicle was obtained from the Army and used to model blast scenarios. The V-Hull model was modified to include a simple bench seat. Three parameter variation studies where performed for this effort. The first was a study of the effects of material thickness on the risk of injury to the tibia during an under body blast event. The second study examined the effects of material thickness on the risk of injury to the lumbar spine during under body blast events. And finally, simulations were performed to analyze the effects of foam padding between the feet and floor during an under body blast event.

Accomplishments

Finite element models of the generic V-Hull and soldier were successfully integrated. Methodologies were developed to investigate the effects of structural component variations and safety measures on the risk of injury to the legs and lumbar spine. These models and software tools can now be used by the Army to evaluate future designs and improve current vehicle designs in an effort to improve occupant safety on and off the battlefield.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period of August 2010 through January 2013 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank-Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. David Tenenbaum served as the project technical monitor and Mr. Eric Sattler served as the TARDEC contracting officer's technical representative.

The authors would like to acknowledge the contribution of the TFLRF technical support staff along with the administrative and report-processing support provided by Dianna Barrera.

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ACRONYMS AND ABBREVIATIONS

IED	Improvised Explosive Device
FEA	Finite Element Analysis
FEM	Finite Element Model
NAVAIR	Naval Air Systems Command
UBB	Under Body Blast
SwRI®	Southwest Research Institute®

1.0 BACKGROUND AND OBJECTIVE

The number of casualties and injuries that occur to war fighters as occupants in U.S. Army tactical vehicles accounts for a large portion overall injury and casualty numbers in the current wars in Iraq and Afghanistan. Designing vehicles and safety systems that will protect the occupants from Improvised Explosive Device (IED) blast and vehicle collisions is made difficult by often competing safety factors. While increasing armor on a vehicle will protect from blast, it will increase the risk of injury in a collision. New tools using the latest in finite element modeling, biomechanics and probabilistic analysis are need to address these challenges.

The objective of this effort is to develop a finite element model of a soldier to be used in identifying and exploring the benefits of safety enhancements in military vehicles. A finite element modeling and simulation assessment will identify key design parameters enabling improvements in design performance of existing and future tactical vehicles. Important scenarios include vehicular collisions, blast/fragment impact, and rollovers, as well as related hazards involving fuel and oil/fluid fires, carbon monoxide leakage, etc. The overall goal is to develop models and methodologies that may determine the relative importance and correlation of vehicle design factors and demonstrate how changes in these design factors can significantly increase the overall safety and survivability of occupants.

2.0 MODELING

2.1 ANATOMICAL MODELING

The foundation of the soldier finite element model is the Naval Air Systems Command (NAVAIR) probabilistic finite element model of the head and spine, Figure 1. The NAVAIR head and spine model has been developed to determine the probability of injury to the soft tissue and bone during +GZ loading events. The model has undergone rigorous verification and validation. A full description of the model can be found in NATO AVT Symposium on Computational Uncertainty in Military Vehicle Design, 2007[1].

Figure 1. The NAVAIR Head and Spine Finite Element Model

Using the NAVAIR spine as the base structure, various anatomical models were created from surface models. The first structure to be added to the model was the rib cage. A surface of the ribs was first meshed and then scaled to fit the existing spine model, Figure 2. The ribs were connected by the use of rigid body constraints between the rib ends and the thoracic vertebrae.

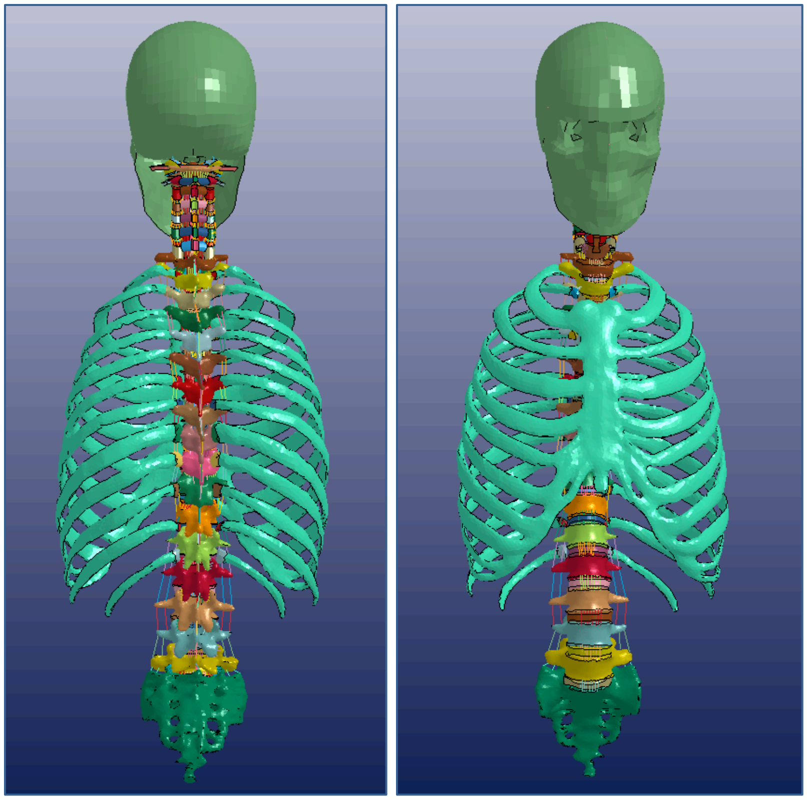

Figure 2. The Final Model of the Ribs and Spine

For the lower limbs of the soldier model, the Southwest Research Institute (SwRI) lower limb model was used. SwRI has developed a high fidelity model of the lower limbs capable of predicting a variety of injuries. The model includes the feet, tibia, fibula, femur, pelvis as well as all the soft tissue associated with the knee and musculature, Figure 3. The femur, tibia and fibula were initially simple rigid element meshes. However, for the purposes of this study, the cortical shell and trabecular cores had to be modeled. New meshes were created for the SwRI lower limb model that included the cortical shell and trabecular core.

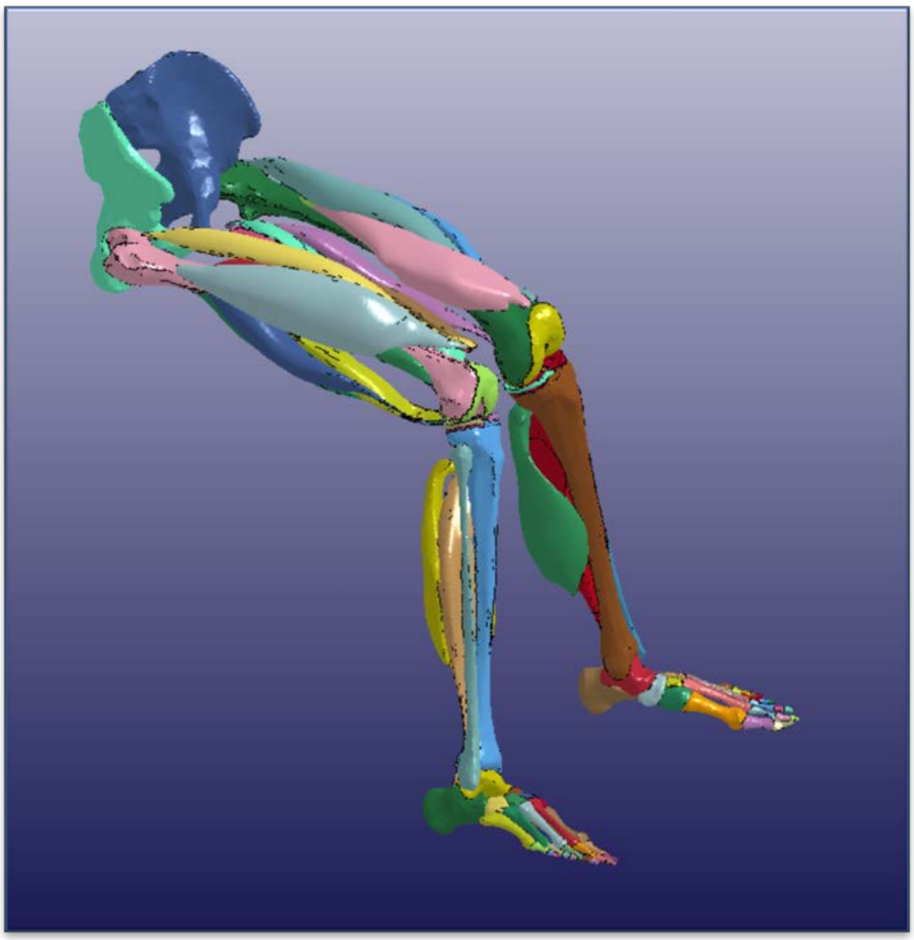

Figure 3. Finite Element Model of the Lower Limbs

Anatomical surfaces of the scapula and clavicle were obtained and added to the model to create connection points for the arm models. Similarly, arms were created by creating volumetric meshes of the humerus, radius, ulna and hand bones. For the arms, hands, scapula and clavicle, the materials were made to be rigid and joints created using computational constraints, Figure 4.

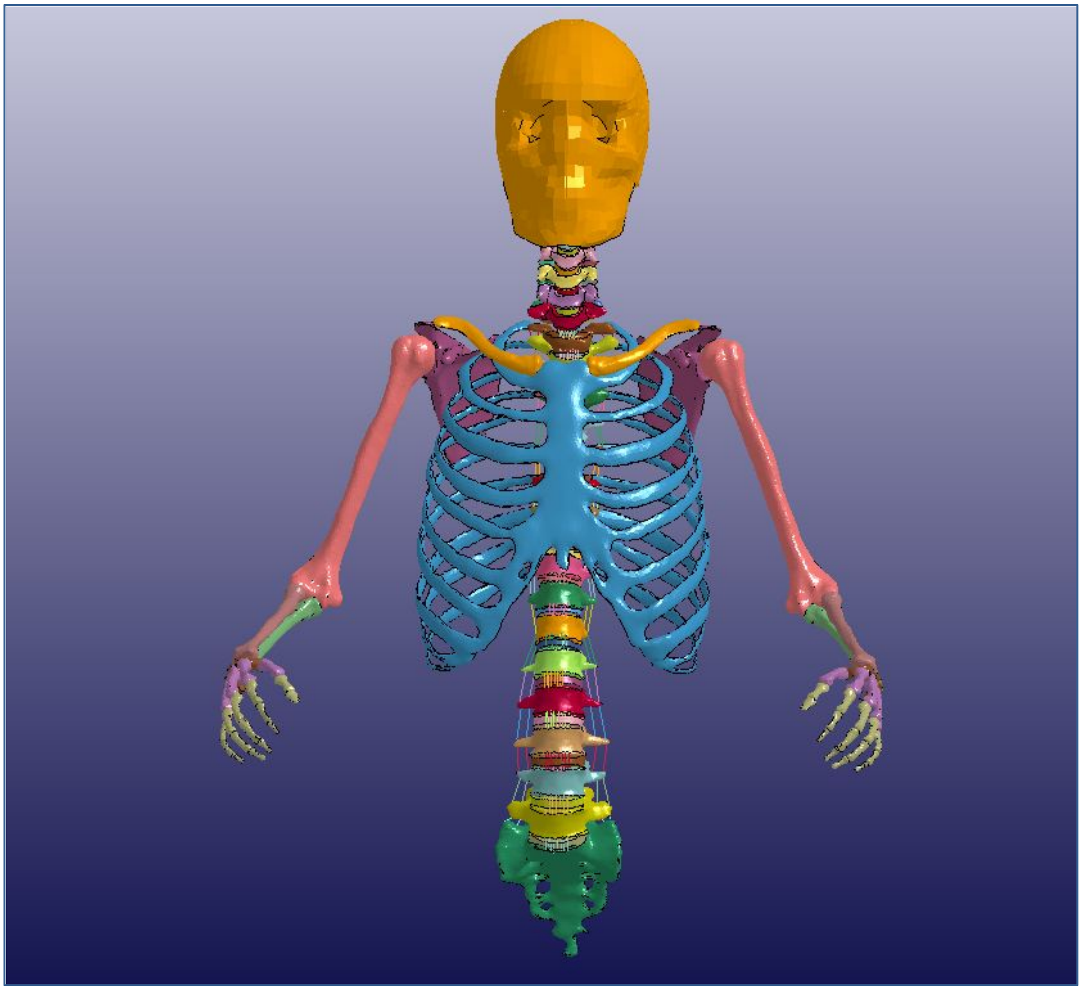

Figure 4. Scapula, Clavicle and Arm Models Attached to the Larger Model

With the skeletal structure complete the internal organs were modeled next. Three dimensional anatomical surfaces of the heart, lungs, liver, stomach and kidneys were obtained and a volumetric mesh created for each. The organs were then added to the soldier model, Figure 5. Finally, a skin surface was created for the model, Figure 6. The final model is a mix of hexahedral and tetrahedral solid elements and triangular shell elements. The model consist of 4918315 elements and 1183403 nodes.

Figure 5. The Full Body Finite Element Model without Skin

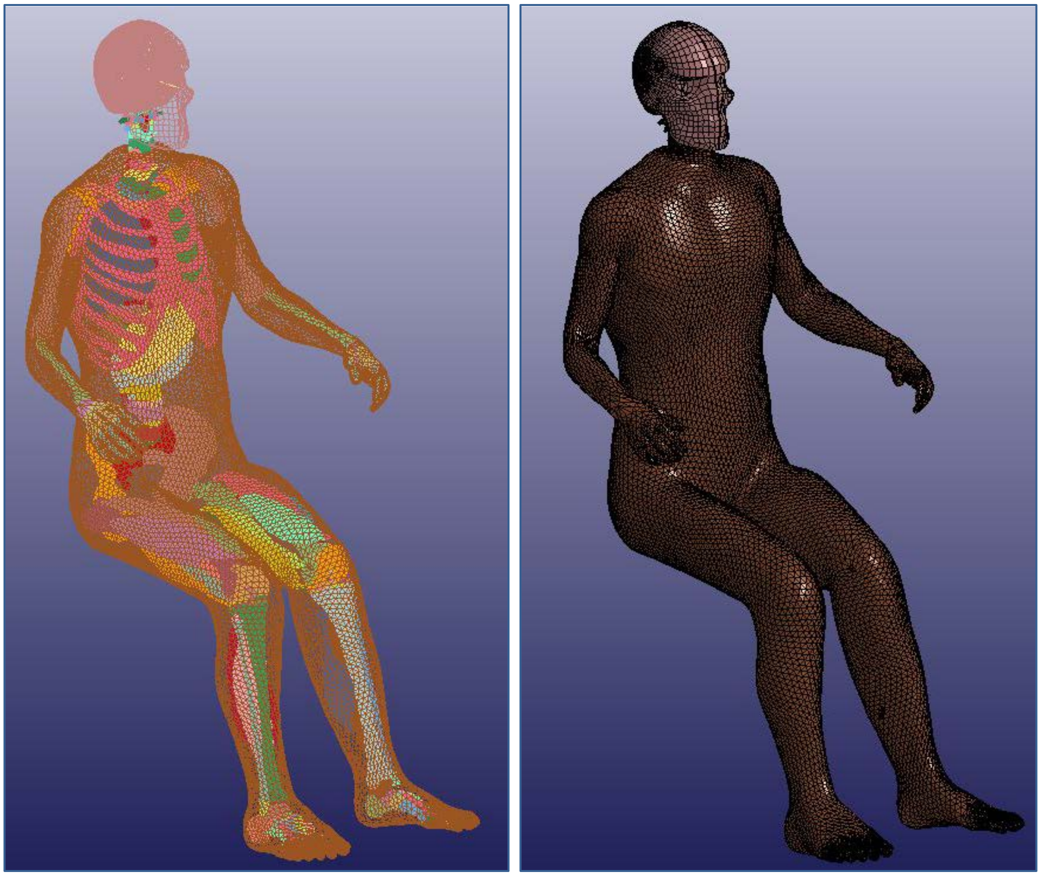

Figure 6. The Full Finite Element Soldier Model with Skin.

2.2 GENERIC V-HULL MODEL

A finite element model of a generic V-Hull vehicle was obtained from TARDEC and modified for the purposes of this program. The model consists of 242242 elements and 242537 nodes. The model was delivered with no seating structures, Figure 7. To enable the analysis of under body blast on vehicle occupants a simple bench seating structure was added to the model. The bench seat was attached to the interior side of the V-Hull structure, Figure 8.

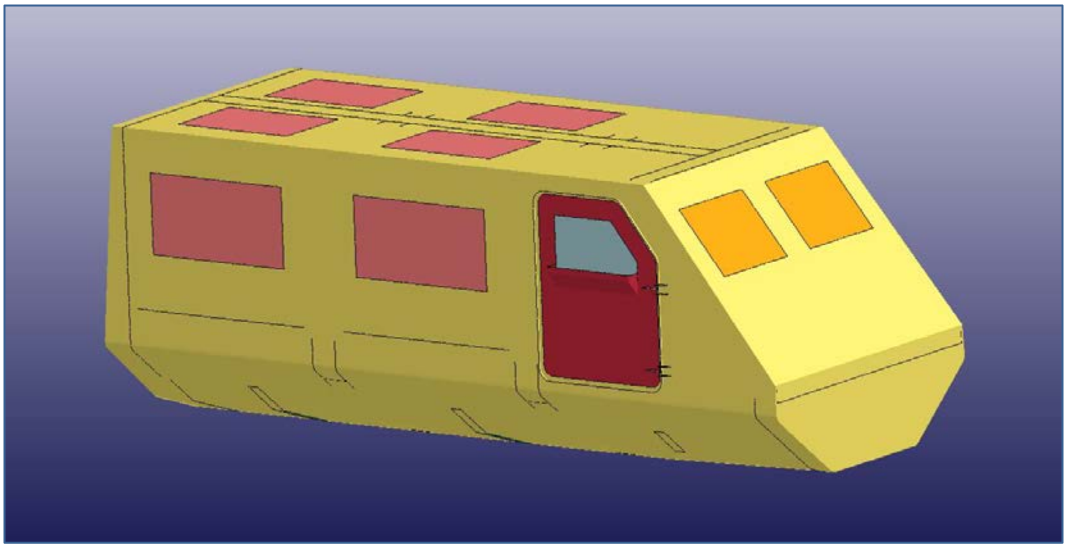

Figure 7. The Generic V-Hull Finite Element Model

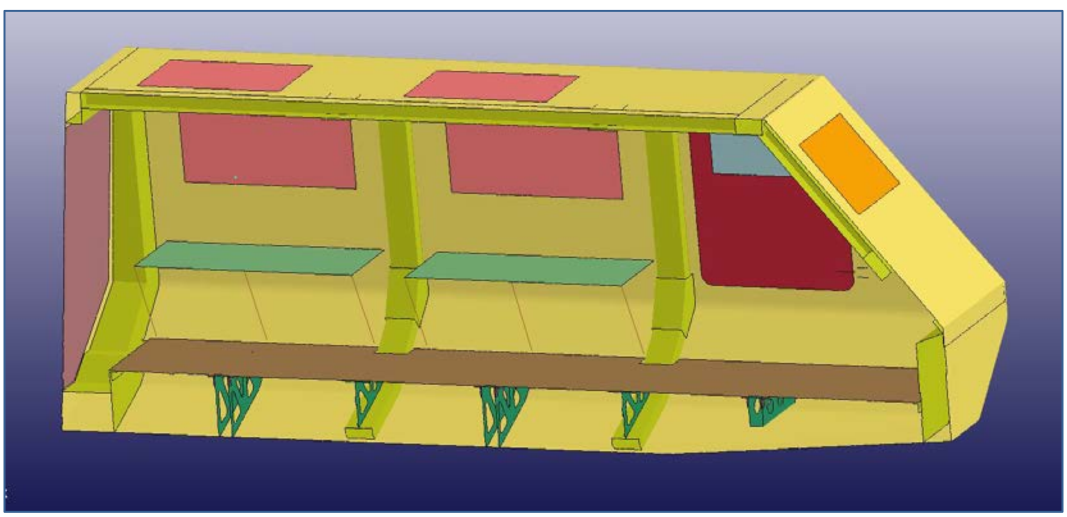

Figure 8. Generic V-Hull Model Cut Away View with the Additional Bench Seat Model

3.0 ANALYSIS AND RESULTS

3.1 UNDERBODY BLAST LOADING

For this study blast loads of 10 and 20 kg TNT were simulated at a distance of 0.2 m below the V-Hull model at the rear. For the simulations, the goal was to have charges large enough to displace the floor of the vehicle, but not too large as to destroy the vehicle or the leg model. It was found that the 10 and 20 kg levels accomplished that goal. Tests simulations were run with the 10 kg and are shown in Figure 9 and Figure 10.

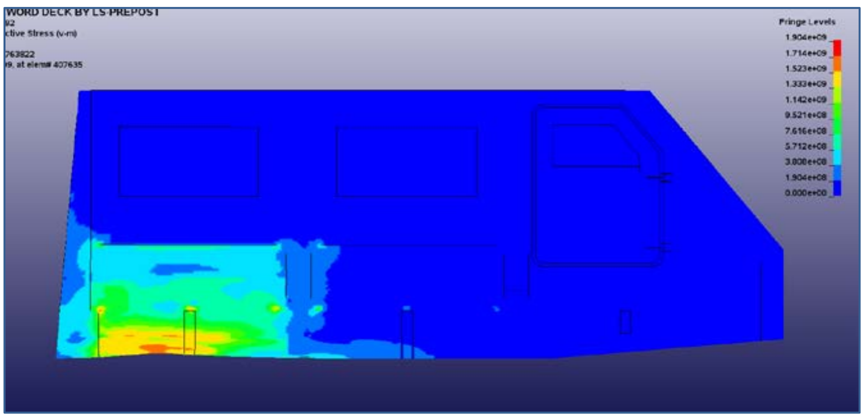

Figure 9. Exterior Model View of the V-Hull with a 10 kg Blast 0.2 m below the rear. Contours are effective stresses (Pa)

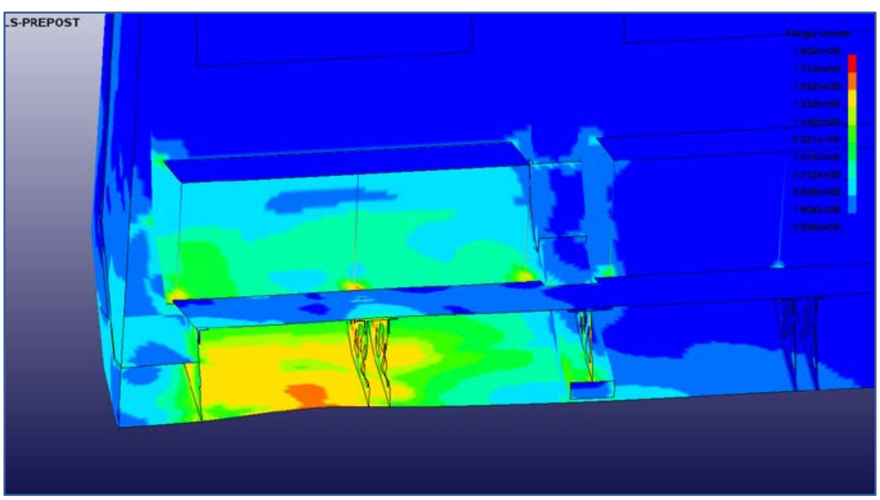

Figure 10. Cut Away Model View of the V-Hull with a 10 kg Blast 0.2 m below the rear. Contours are effective stresses (Pa)

3.2 TIBIA FORCE STUDY

Under body blast events often result in fracture to the lower limbs, specifically the tibia. During the blast, the velocity and force of the floor impacting the feet of the soldiers may result in large compressive forces. The forces that result foot and ankle injury where developed by Yoganandan[2] and can be shown as injury risk curves. The tibia force that results in injury is a function of age. Figure 11 presents risk curves for 25, 45 and 65 years old.

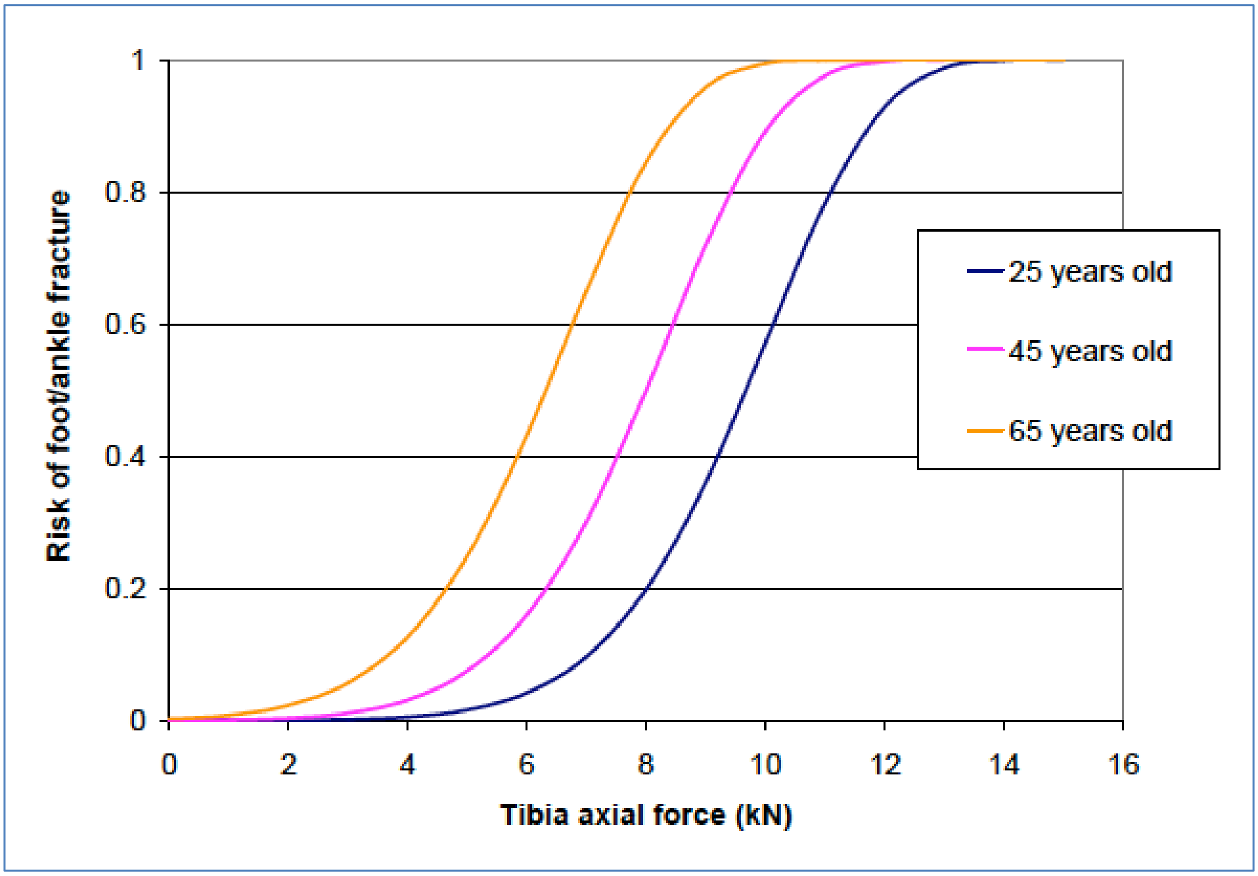

Figure 11. Foot and Ankle Injury Risk Curves as Computed by Yoganandan[2]

For this study only the pelvis and leg model were used with a 33 kg mass to simulate the torso mass of the soldier. The pelvis and legs were positioned on the bench seat of the vehicle model with the feet contacting the floor. A 10 kg blast was applied at 0.2 m under the hull where the model was positioned. To determine the effects of varying the thickness of the vehicle structures, the blast load was chosen in order to prevent fracturing of the tibia. Forces were recorded throughout the event and then used to determine the effects of the parameter variation. The thickness of the floor, support truss and hull were each increased by 10% and run independently. Figure 12 shows the position of the leg model and identifies the truss, floor and hull.

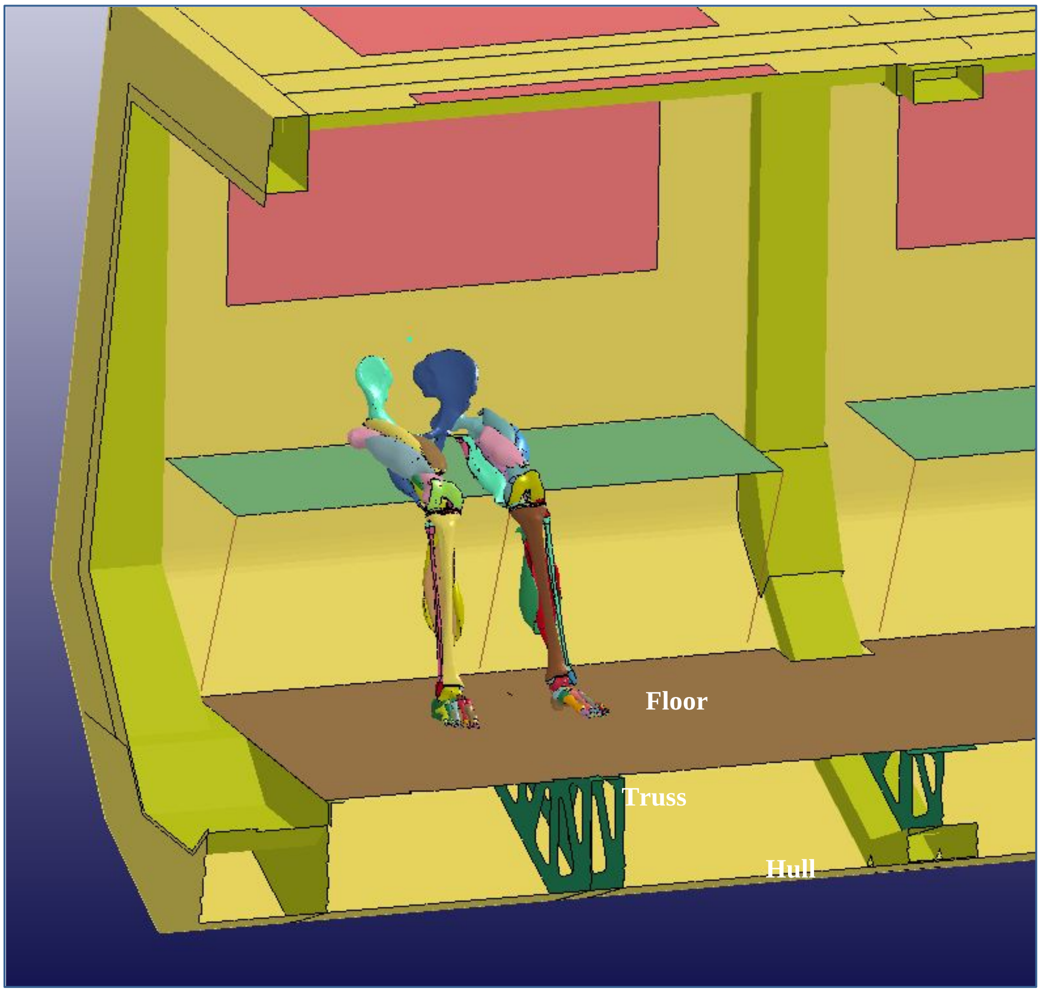

Figure 12. Cut away view of the Model identifying the Hull, Truss and Floor

The results of the study reveal that increasing the thickness of the hull decreases the tibia force by 6.4%. Interestingly, increasing the thickness of the truss by only 10% results in a 12.9% increase in tibia force. The truss acts as an energy absorption device and by increasing the thickness the rigidity is also increased, allowing the force from the hull to be transferred into the floor more readily. Finally, increasing the floor thickness had no effect on tibia forces. The results are shown in Figure 13, Figure 14, and Figure 15.

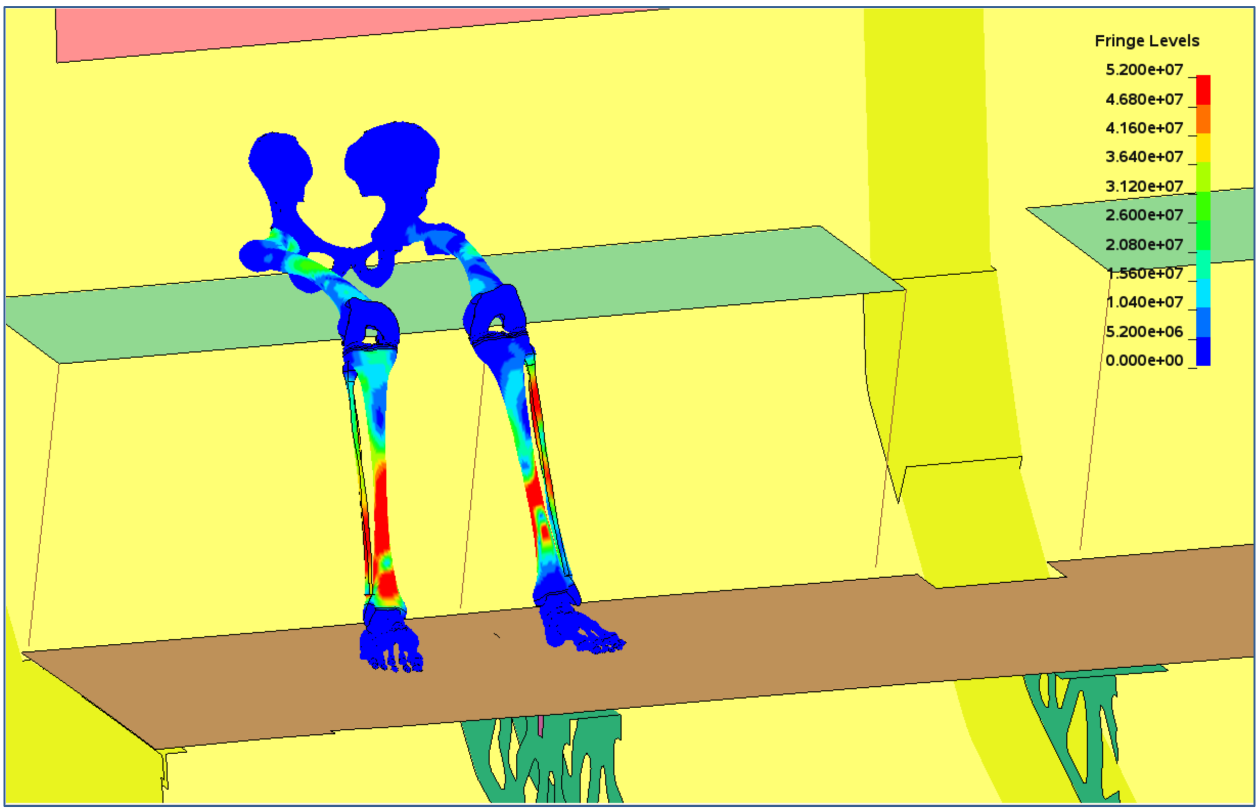

Figure 13. Under body blast simulation with the loaded legs.
The contours show effective stress (Pa)

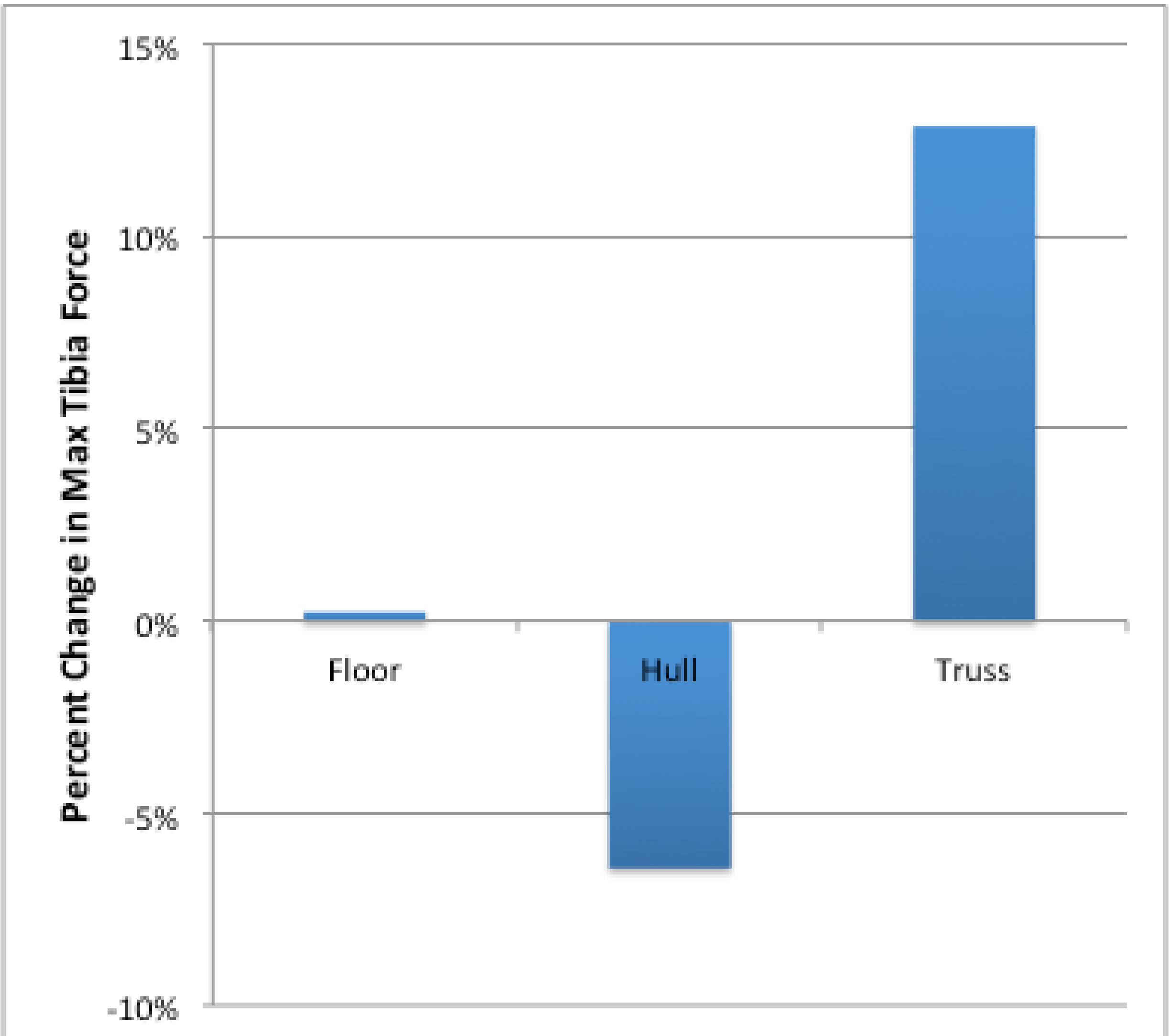

Figure 14. Parameter variation study results, Show that increasing the thickness of the hull decreases tibia forces while increasing the thickness of the support truss increases tibia forces

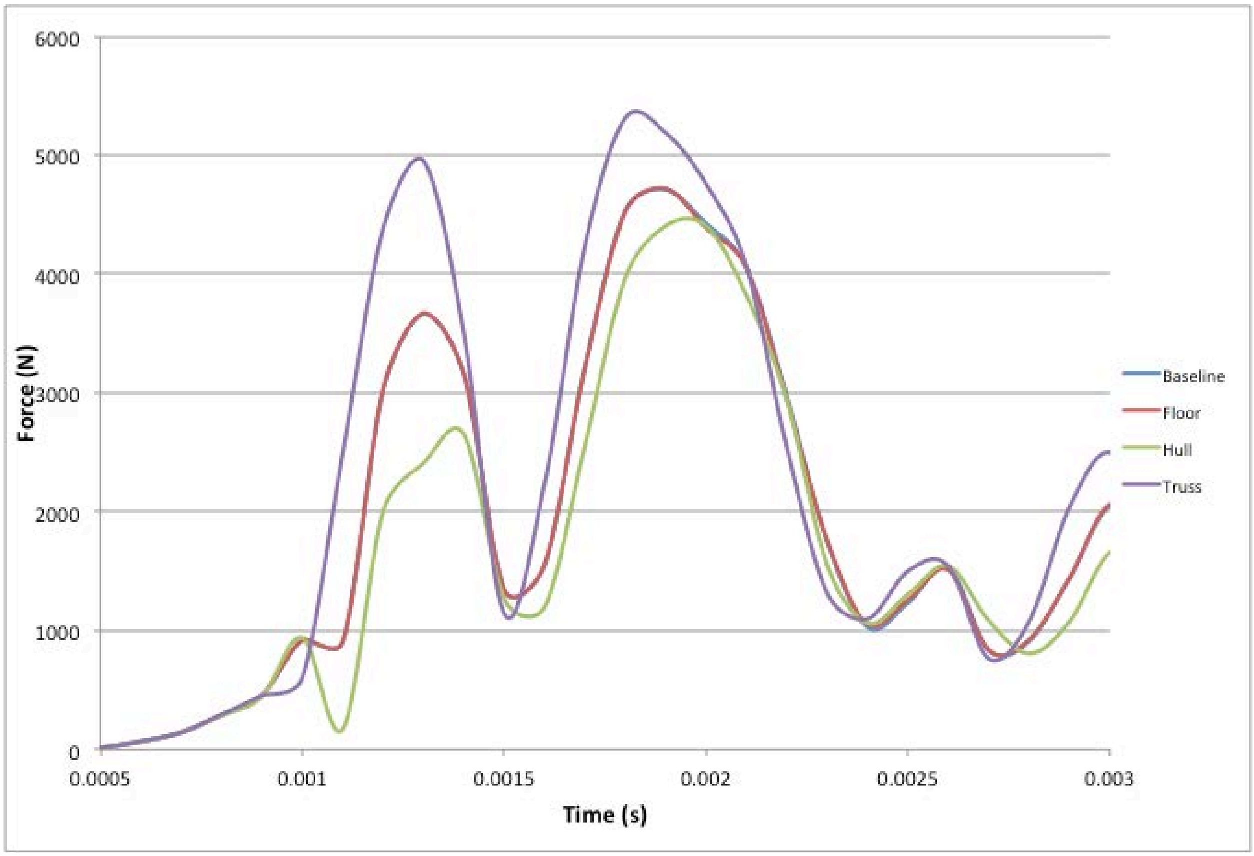

Figure 15. Tibia force time histories. The floor and baseline plots are coincident

3.3 FOAM STUDY

One injury mitigation device used to reduce the forces in the lower limbs during a blast event is foam padding on the floor. The purpose of this study was to demonstrate how the models developed for this program can be used to quantify the effectiveness of different types of foam between the soldiers feet and the floor. For this study a 20 kg TNT blast was simulated at 0.2 m below the rear of the vehicle with the leg and pelvis model positioned on the bench seat with a 33 kg simulated mass, Figure 16. First a baseline simulation was performed with no pad which resulted in the fracture of the tibia, Figure 17. The foam pad was then added and a baseline stiffness of 2.0e6 Pa was analyzed and then increased by 25 and 50% to determine the effect of foam stiffness.

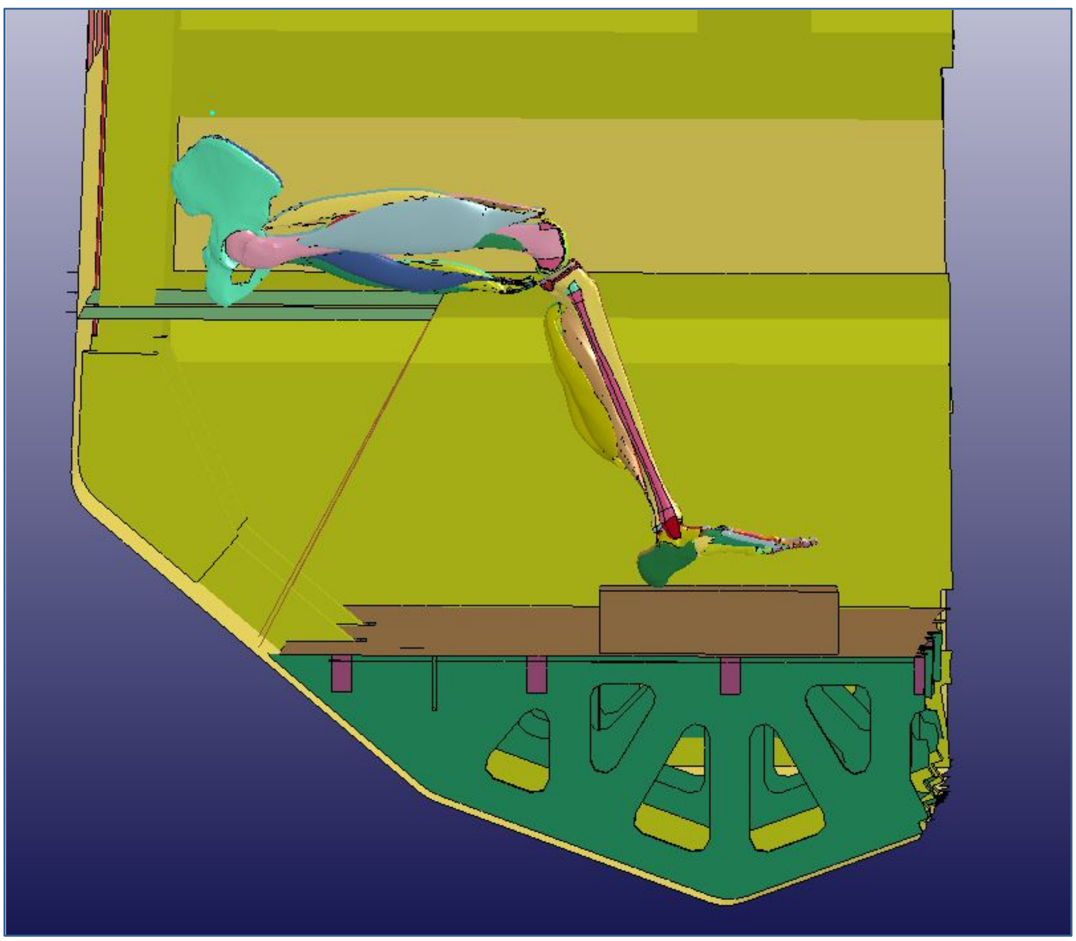

Figure 16. Cut away view of the leg model with a foam block between the heel and floor

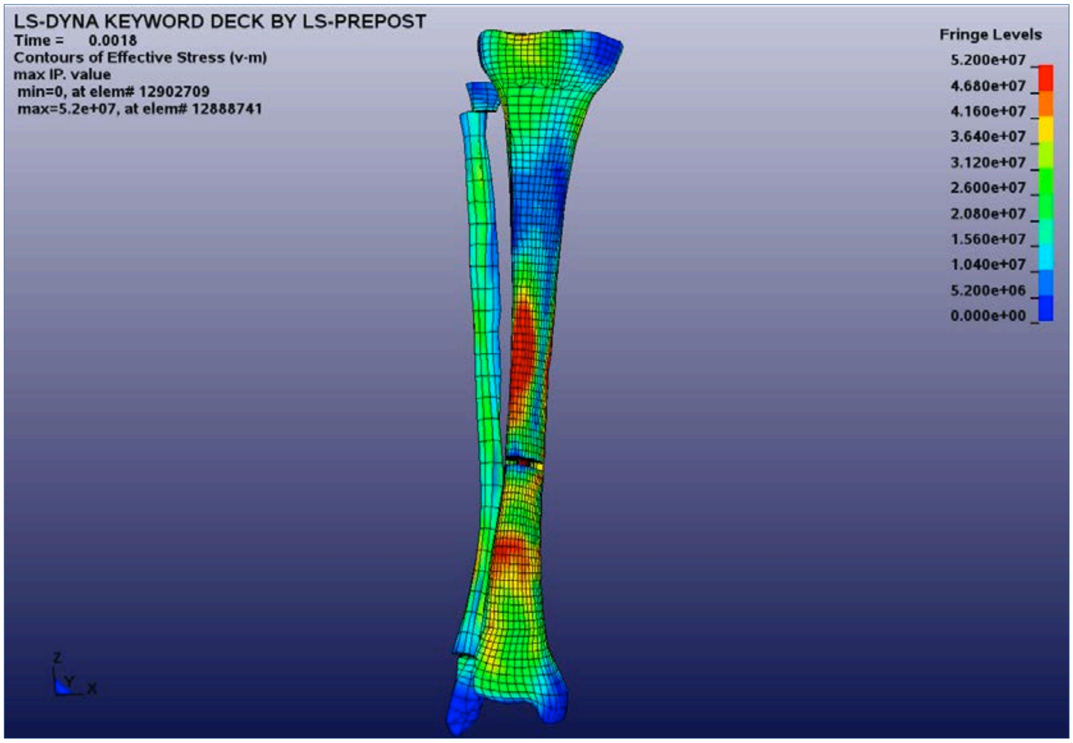

Figure 17. Results of the 20 kg blast without a foam pad
The tibia and fibula both fracture

The results of the study show that the addition of the foam reduce the tibia forces by at least 35%. The reduction is likely higher since the tibia and fibula fractured in the baseline analysis therefore limiting the amount of force that was allowed in the tibia. The results for the foam stiffness variation study are not as straight forward. The time history plot of tibia forces presents two peak forces during the blast event, Figure 18. The first peak clearly show that the stiffer the foam the higher the force. The second peak shows that the base stiffness of foam results in the lowest tibia forces, however the 50% increased stiffness yield a slightly lower force than the 25% increased stiffness foam. These results illustrate the complex nature of these simulations and the need to perform such simulations when considering design changes.

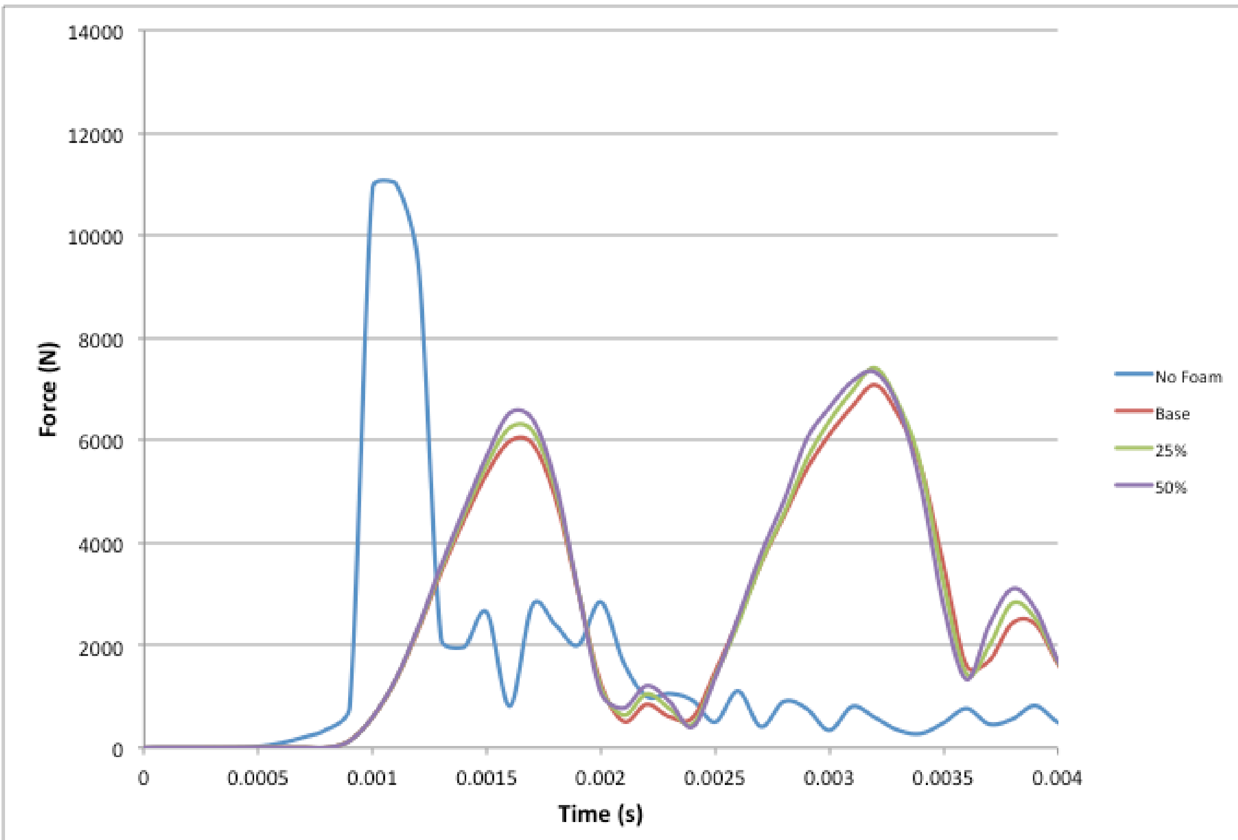

Figure 18. Force time history of the tibia for the 20 kg under body blast without foam and various foam stiffness

3.4 LUMBAR INJURY STUDY

Apart from injury to the lower limbs, injury of the lumbar spine during underbody blast is common. Similar to the tibia force study in Section 3.2, the effects of varying material thickness on lumbar forces was investigated. For this study, only the lumbar model was used with a 33 kg mass to simulate the torso mass of the soldier. The lumbar was positioned on the bench seat of the vehicle model with the pelvis contacting the bench. A 10 kg blast was applied at 0.2 m under the hull where the model was positioned. The L5-Sacrum disk forces were recorded throughout the event and then used to determine the effects of the parameter variation. The thickness of the floor, support truss and hull were each increased by 10% and run independently. Figure 19 shows the position of the lumbar model.

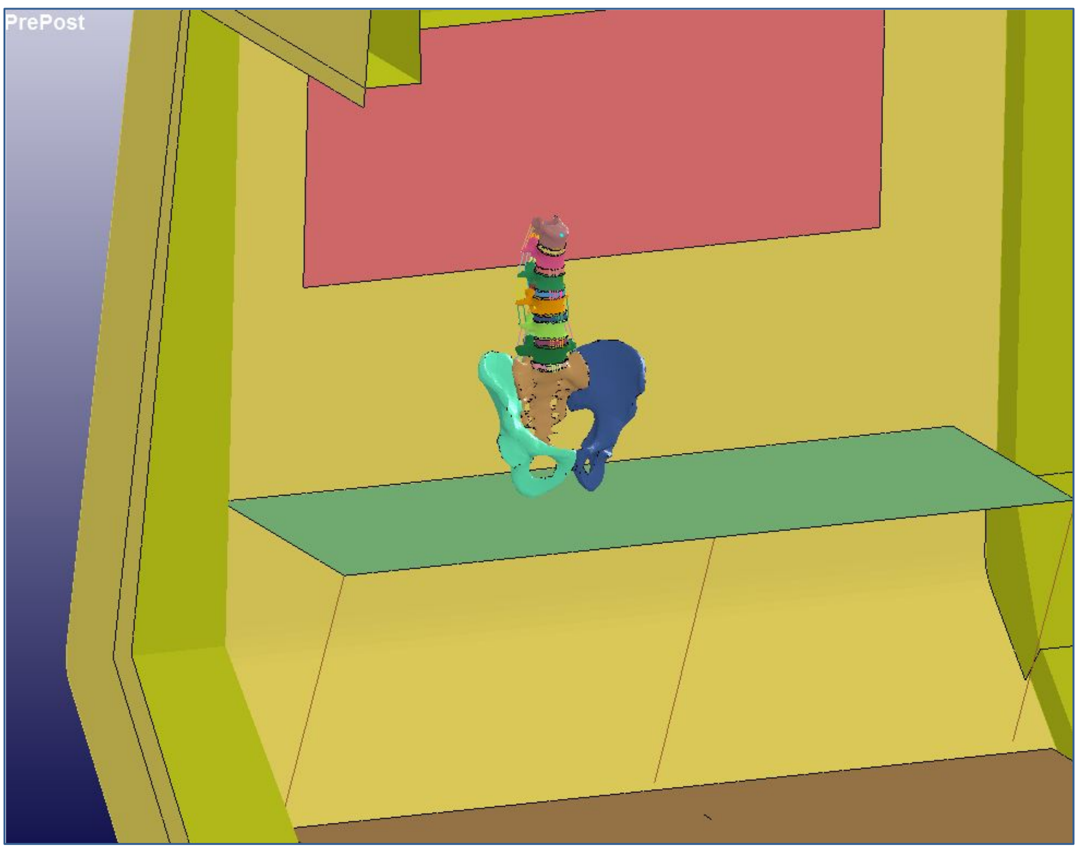

Figure 19. Lumbar and pelvis model used in the parameter variation study

Much like the tibia forces study, the results show that increasing the thickness of the hull decreases forces experienced in the lumbar while increasing the truss and floor thickness only marginally change the forces, Figure 21. The 10% increase in the hull thickness results in a decrease in force of 8.9%, Figure 20. Increasing the truss thickness by 10% increases the lumbar forces by 1.6%. Finally, increasing the floor thickness by 10% decreases lumbar forces by 1.5%. It should be noted that the simulations were able to show injury in the lumbar in the form of vertebral height loss of L5, Figure 22.

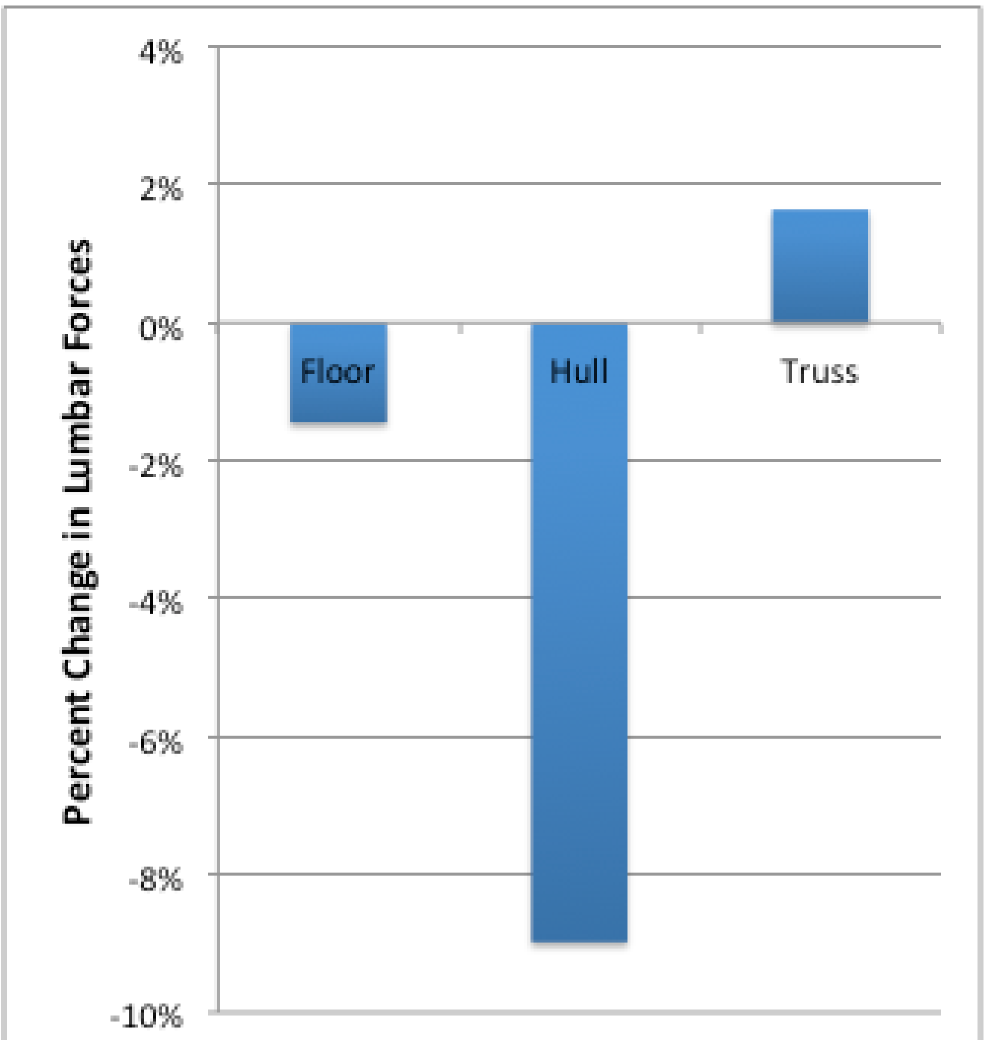

Figure 20. Parameter variation study results. Show that increasing the thickness of the hull and floor decreases tibia forces while increasing the thickness of the support truss increases tibia forces

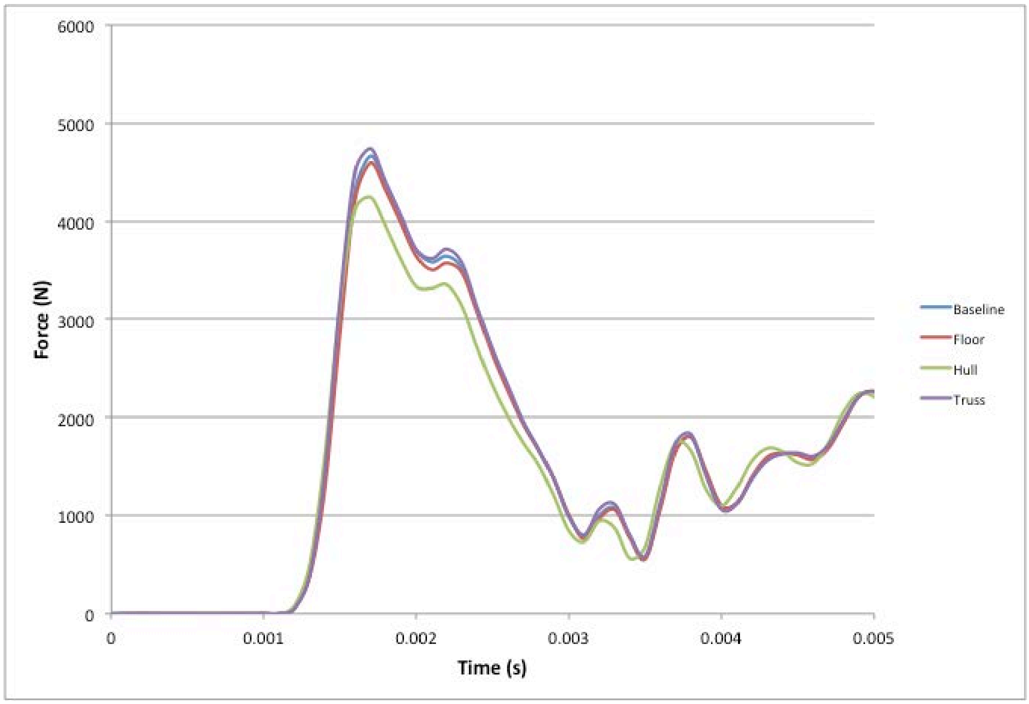

Figure 21. Lumbar force time histories

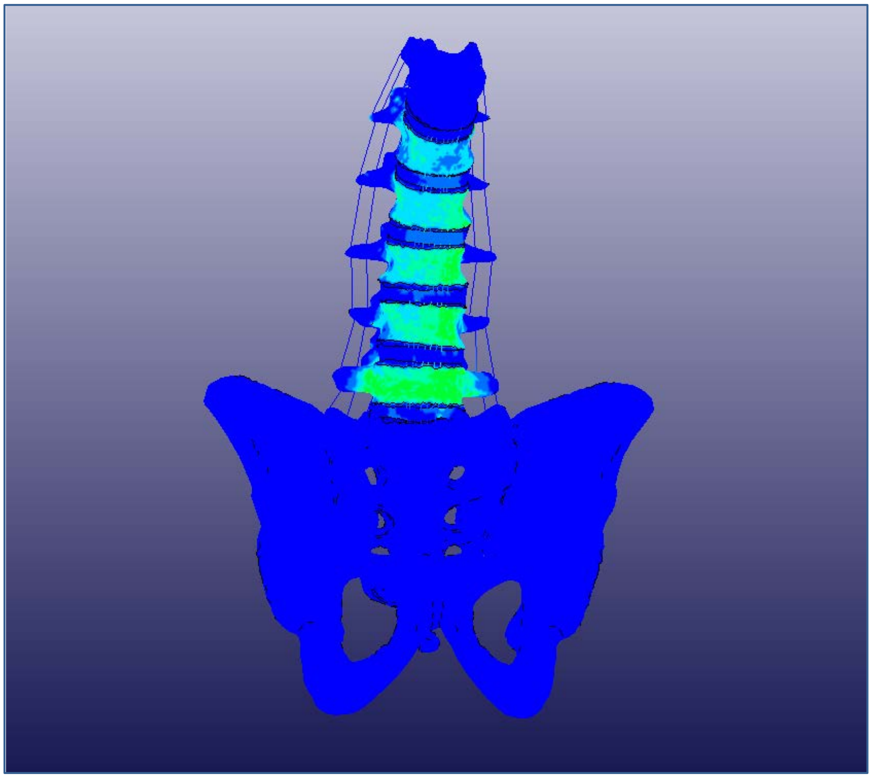

Figure 22. Stress contours of the lumbar spine under load L5 is being permanently deformed in this state.

4.0 CONCLUSION AND DISCUSSION

The objectives of this program were to develop a finite element model of the soldier and develop methodologies using the finite element models developed in the program to assist in the assessment of vehicle designs. The three design studies performed in this program illustrate that biomechanical finite element models can be a powerful tool in evaluating designs and mitigating the risk of injury for military vehicle occupants.

Limitations of this program are verification and validation of the soldier model and its components as well as the accuracy of the generic V-Hull model. The NAVAIR cervical, lumbar and thoracic spine that was used in this program underwent a rigorous verification and validation process. However, the other components of the model have not. Significant work needs to be performed in order to validate the complete soldier model. Component validation is required for the organ tissues, legs, arms, and ribs, followed by more complex system validations of the completed model. Without the verification and validation the model can be used to develop methodologies and possibly compare designs, however, it cannot be used to accurately predict injury for components other than the spine. Furthermore, the generic V-Hull model is for public use and does not contain accurate material properties. For accurate risk of injury simulations the vehicle model would need to have undergone the same verification and validation process as the the NAVAIR spine model.

In conclusion, a high fidelity finite element model of a soldier have been created. Components of the soldier model have been analyzed in a number of design studies using an under body blast loading condition and the generic V-Hull model. The completed soldier model combines the NAVAIR spine and head with the SwRI leg model with models of the ribs, internal organs and arms that were created for this program. The design studies performed in this program have shown how quickly these models can be adapted to inform important design changes and determine the changes in risk of injury when designing mitigation devices.

5.0 REFERENCES

[1] Thacker, B., Francis, W., Nicolella, D., "*Model Validation and Uncertainty Quantification Applied to Cervical Spine Injury Assessment*". NATO AVT Symposium on Computational Uncertainty in Military Vehicle Design, 2007.

[2] Yoganandan, N., Pintar, F.A., Boyton M., Begeman, P., Prasad, P., Kuppa, S.M., Morgan, R.M. and Eppinger, R.H. (1996), Dynamic Axial Tolerance of the Human Foot-Ankle Complex, 962426, Society of Automotive Engineers, Warrendale, PA, USA.